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Investigation of the Stability of Maxillary Posterior Downward and Forward Movement by Using Finite Element Analysis: Methodological Study

Maksiller İlerletmeyle Beraber Posterior Sarkıtmanın Stabilitesinin Sonlu Elemanlar Analizi ile İncelenmesi: Metodolojik Çalışma

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This study was presented as an oral presentation at Turkish Oral and Maxillofacial Surgery Association Congress, May 11-15, 2022, Antalya, Türkiye.

ABSTRACT Objective: The maxillomandibular complex's counterclockwise movement with maxillary advancement and posterior downward repositioning was considered as one of the most unstable movements in orthognathic surgery. This study examines the reliability of fixation of different plate-screw systems in grafted and non-grafted models in the counterclockwise rotation where the maxilla is positioned anteriorly with posterior downward movement. **Material and Methods:** Stress distribution has been examined in four maxilla models. The transportable segment was moved 5 mm forward and posteriorly 4 mm downward in all models. Two scenarios with and without graft applied to the posterior region were created. These two scenarios were fixed with 2.0- and 1.5-mm diameter osteosynthesis systems. Four forces were applied separately to these models (45 and 125 N to the incisive tooth, 110 and 250 N to the molar tooth). Stress distribution on the bone and osteosynthesis screw plate system were examined in all models. **Results:** The application of graft decreased the load distribution on the bone and osteosynthesis systems. The stress distribution of both plate systems in the grafted models was similar in bone and osteosynthesis systems. The highest stress was measured in the non-grafted model using the 1.5 osteosynthesis system (Screw-F, 249.81 N/mm^2), while the lowest stress was measured in the 2.0 system (Screw-G, 0.49 N/mm^2) with the graft-applied model. **Conclusion:** The study results support the view that it is predicted that the necessity of graft application in surgeries where the maxilla is downward posteriorly with advancement. The 1.5 mm diameter system can be used safely if a graft-applied to the posterior gap.

Keywords: Orthognathic surgery; Le Fort I; finite element analysis; counterclockwise rotation; maxillary downward movement

ÖZET Amaç: Ortognatik cerrahi stabilizasyonunda maksillomandibular kompleksin hem saat yönü tersine hareketi hem de maksillanın inferiorda repoze edilmesi en güvensiz kabul edilen hareketlerden biridir. Çalışmanın amacı, maksillanın posterior sarkıtma ile anteriorda konumlandırıldığı saat yönü tersi hareketinde greftli, greftsiz ve farklı plak-vida sistemlerinin fiksasyonda güvenilirliğini incelemektir. **Gereç ve Yöntemler:** Çalışmada oluşturulan 4 maksilla model üzerinde stres dağılımı incelendi. Bütün modellerde hareketli segment 5 mm ilerletilerek posterior bölgeden 4 mm sarkıtıldı. Posterior bölgeye greft uygulanan ve uygulanmayan 2 senaryo oluşturuldu. Bu 2 senaryo hem 2,0 hem de 1,5 mm çaptaki osteosentez sistemleri ile fikse edildi. Oluşturulan bu modellere 4 farklı kuvvet ayrı ayrı uygulandı (insiziv dişe 45 N ve 125 N, molar dişe 110 N ve 250 N). Modellerde hem osteosentez vida plak sistemi hem de kemik üzerindeki stres dağılımı incelendi. **Bulgular:** Çalışmada greft uygulanmasının kemikte ve osteosentez sistemleri üzerinde yük dağılımını azalttığı bulundu. Greft uygulanan modellerde tüm plak sistemlerinin kemikte ve osteosentez sistemlerinde stres dağılımının birbirine yakın olduğu bulundu. En yüksek stres 1,5'lik osteosentez sisteminin kullanıldığı ve greft uygulanmayan modelde (Vida-F, 249,81 N/mm^2), en düşük stres ise 2,0 sistemin kullanıldığı ve greft uygulanan modelde ölçüldü (Vida-G, 0,49 N/mm^2). **Sonuç:** Maksillanın posteriordan sarkıtıldığı ameliyatlarda greft uygulanmasının gerekliliği, eğer greft uygulanmış ise 1,5'luk sistemin de güvenle kullanılabileceği öngörülmektedir.

Anahtar Kelimeler: Ortognatik cerrahi; Le Fort I; sonlu elemanlar analizi; saat yönü tersi rotasyon; maksiller sarkıtma

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Le Fort I Osteotomy (LFIO) is one of the most widely used treatments for the aesthetic and functional correction of maxillofacial deformities such as maxillary hypoplasia.[1,2] Although LFIO has many advantages, inferior positioning of the maxilla has some challenging considerations. One of the main problems with this movement is postoperative stability. It has been established as one of the least stable movements.[1,3] Also, it has been argued that the graft should be applied between bones in the osteotomy line if there is more than 3 mm downward movement.[4]

Counterclockwise rotation (CCWR) of the maxillomandibular complex has quickly become a valuable surgical planning tool. Research on CCWR has shown a considerable positive effect by increasing the oropharyngeal airway and improving facial balance.[5] Questions have been raised about the stabilization safety of the CCWR due to an increase in posterior facial height, stretching of the suprahyoid, pterygoid, and masseteric muscles, and its negative effect on the temporomandibular joint.[1,5]

It is well established that finite element analysis (FEA) is a trustworthy method and provides quantitative data about stress distribution. It can be used to understand the mechanical behavior of complex materials in the virtual platform.[6,7] The key aspect of FEA in maxillofacial surgery is answering many technical questions that cannot be obtained in the operating room. In addition, there are many advantages, such as comparing different methods without any harm and predicting the problems that may occur.[8,9]

The aim of this study was to develop a better understanding of the bone and osteosynthesis system's distribution of stress in posterior downward movement with CCWR and seek to obtain data that will help to address research gaps. In addition, it was aimed to evaluate the effect of the plate systems (2.0 and 1.5) and the posterior graft application's influence on the stress distribution in the maxillofacial region. The null hypothesis of the study was that in grafted cases, both 1.5 and 2.0 mm osteosynthesis systems have similar stability.

MATERIAL AND METHODS

Ethical approval was provided by İstanbul Medipol University's institutional ethical committee (date: March 10, 2020, no: 10840098-604.01.01-E.12199) in accordance with the principles of the Declaration of Helsinki. A random sample of a patient with maxillomandibular deformity was obtained from the İstanbul Medipol University Medipol University Mega Hospital computerized tomography image archive.

The first step in this process was to make the 3D mesh structures more homogeneous. Data management, adjustment, and analysis were performed using Activity 880 optical scanner (Smart Optics, Germany), Rhinoceros 4.0 (Robert McNeel & Associates, USA), VRMesh Studio (VirtualGrid Inc, USA), and Algor Fempro analysis software (ALGOR Inc, USA).

Maxilla models were created geometrically, and cortical, cancellous bone layers and tooth structures were modeled and introduced to the software. Material values (elasticity module and Poisson's ratio) identifying their physical properties were assigned to each of the structures forming the models (Cortical shell: E=13.7 GPa, Poisson ratio=0.3, Spongious bone: E=1.37 GPa, Poisson ratio=0.3).[10] All models were considered linear, homogeneous, and isotropic materials. After the refinement processes on the obtained maxilla model, the solid meshing process of the maxilla was completed.

Four models were created. In all models, 5 mm advancement and 4 mm posterior downward movement were performed (Table 1). The experiments were run using the fixation system used in the models was designed following the 1 mm (2.0 mm width) and 0.6 mm (1.5 mm width) thick sets of KLS Martin Group (Germany). 4-plates and 16-screws were placed in the piriform aperture and the maxillary buttress area. A medium size four-hole L plate with 7 mm long screws of the relevant system (micro or mini screw) was used for osteosynthesis.

In order to investigate the effects of different types of bite forces, four different scenarios were conducted for each model. The 45 N and 125 N static forces were applied to the incisor tooth. In addition, 110 N and 250 N forces were applied to the first molar. The design of the different forces on the same tooth was based on imitating the early or late postoperative period. All forces were applied parallel to the

TABLE 1: Model list.

Model No	Graft	Osteosyynthesis System	Horizontal Movement	Vertical Movment
1	(-)	2.0 mm	5 mm Adcanvement	4 mm Downward
2	(+)	2.0 mm	5 mm Advancement	4 mm Downward
3	(-)	1.5 mm	5 mm Advancement	4 mm Downward
4	(+)	1.5 mm	5 mm Advancement	4 mm Downward

tooth-long axis. The forces were applied to the central sulcus in the first molar tooth. In the incisive tooth, forces were applied directly to the biting edge.

Standardized points were also determined on models to objectively observe the effects of different scenarios. Stress values obtained from these points were noted, and this process was repeated for osteosynthesis systems.

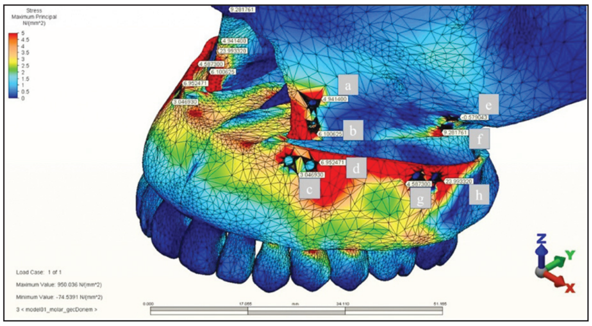

FIGURE 1: Standardized evaluation points of bone.

RESULTS

The first set of analyses examined the impact of bite forces on the bone with the minimum and maximum principal stress values. The next section of the assessment was concerned with osteosynthesis systems. Furthermore, fixed points were determined in each model (Figure 1) and osteosynthesis system (Figure 2, Figure 3) to standardize the data assessment.

The stress values on the standardized points of bone induced by four different forces applied in all models are shown in Figure 4.

45-N AND 125-N INCISOR BITE FORCE

Both forces gave similar results according to stress distribution pathways on grafted and non-grafted models. Higher minimum and maximum principal stress were observed around the screws in the molar region in the non-grafted models. In grafted models, this region was not affected by the bite force from the incisor teeth. Instead of that, the graft made stress pass perpendicular to the bone and created stress on the non-transport segment of the maxilla. Otherwise,

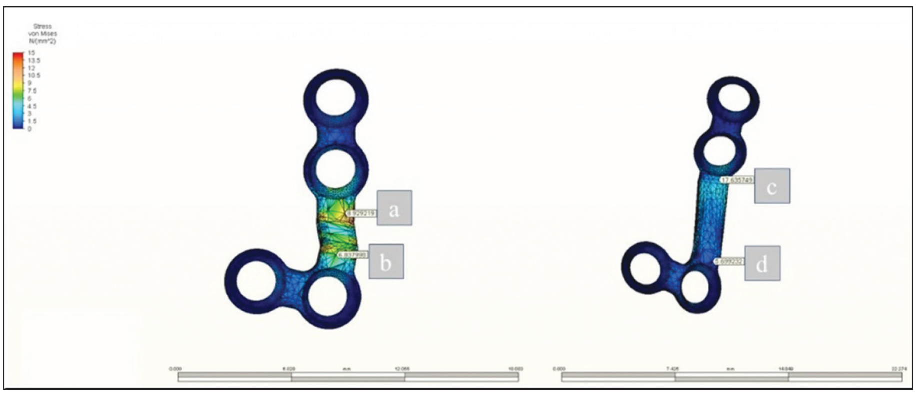

FIGURE 2: Standardized evaluation points of plate. “a” and “b”: anterior plate, “c” and “d”: posterior plate.

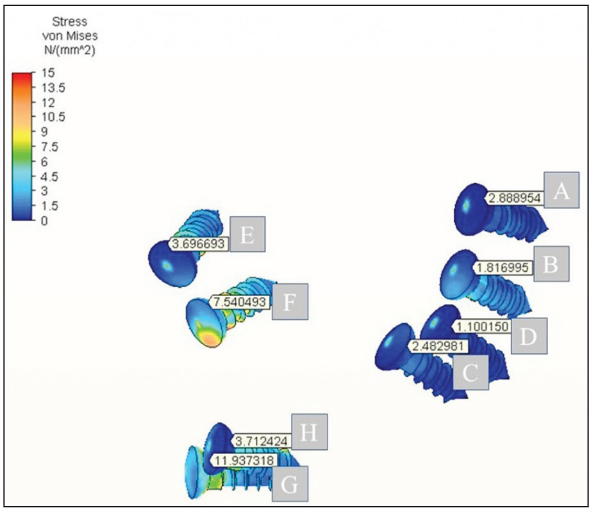

FIGURE 3: Standardized evaluation points of screws (A-D: anteriors screws, E-H: posterior screws).

higher stress accumulation was detected at anterior bone contact in the non-grafted models.

Between osteosynthesis systems, results were found to be similar. 1.5 mm diameter screw-plate system demonstrates more stress accumulation than 2.0 mm. The anterior plate accumulates more stress than the posterior under incisor forces.

110-N AND 250-N MOLAR BITE FORCE

The data inspection in grafted models showed that the forces were perpendicularly transmitted to the viscerocranium. In the non-grafted models, the stress was transmitted more diagonally toward the anterior bone contact. As a result, it generates more stress accumulation in the anterior bone contact and the bone around the screws in non-grafted models (Figure 5).

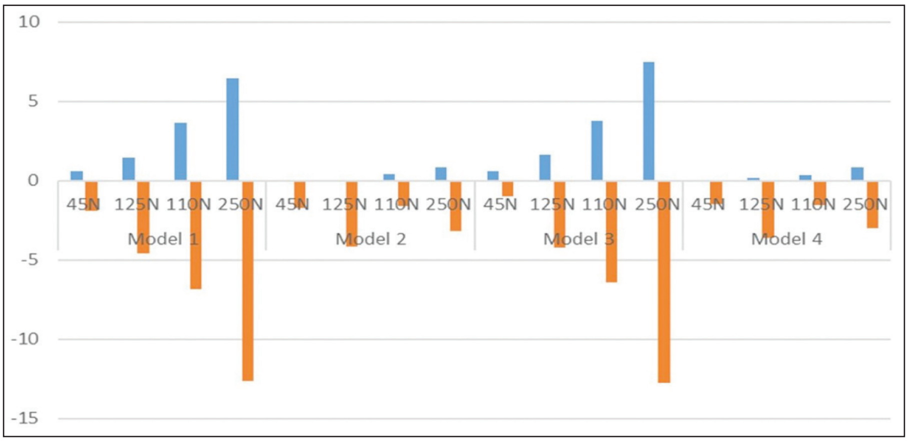

FIGURE 4: Mean maximum (blue) and minimum (orange) principal stress values (N/mm2) of Standardized bone evaluation points.

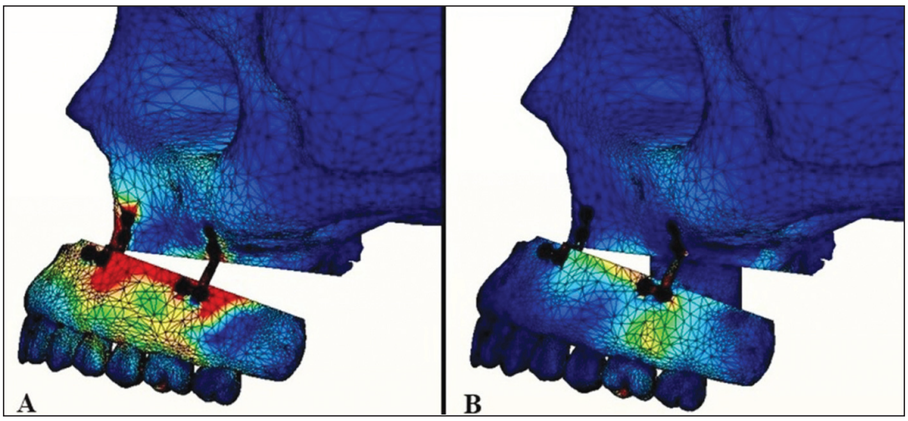

FIGURE 5: A; Model 1, 250 N force, maximum principal stress (lateral view), **B;** Model 2, 250 N force, maximum principal stress (lateral view).

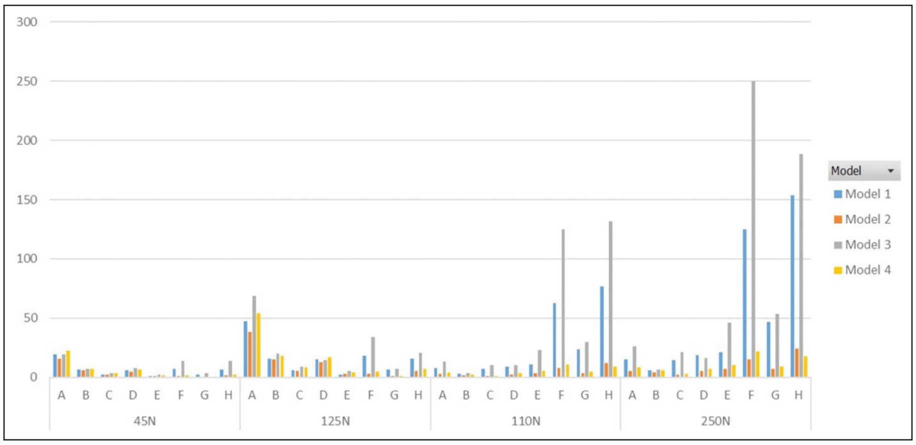

FIGURE 6: von Mises stress values (N/mm²) of standardized screw evaluation points.

Although the non-grafted models' minimum and maximum principal stress values were quite close, the stress accumulation on the bone was less in the 2-0 system. The stress in the grafted models was considerably lower than in the non-grafted models. Closer inspection of the nasal floor has shown that non-grafted models had noticeably more stress than grafted models under 250-N bite force.

The highest maximum and minimum principal stress value (17.855 N/mm², -44.987 N/mm²) was found in model 3 on Point-H under 250 N force and minimum principal stress value.

OSTEOSYNTHESIS SYSTEMS

The highest Von mises stress was 249.81 N/mm² on Screw-F of the posterior plate under 250 N bite force in Model 3. The lowest Von mises stress was measured 0.49 N/mm² on screw-G of the posterior plate under 45 N bite force in Model 2 (Figure 6).

In the inspection of mean screw stress for all scenarios, screw-F had the highest accumulated stress. Screw-H's mean von Mises value was also close to Screw-F. The lowest stress was determined in screw-C (Figure 7).

An inspection of the stress in standardized plate points were showed that in model 3 (250 N force), plate-c has the most stress accumulating point with 348.78 N/mm² (Figure 8). Mean von Mises values of all scenarios comparison also confirmed that plate-c is the most stress-accumulating point (Figure 9).

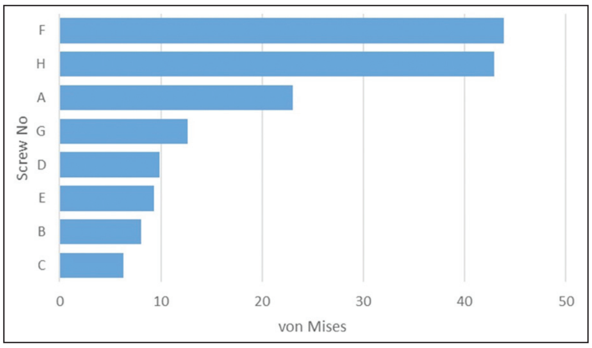

FIGURE 7: Mean von Mises (N/mm²) values of screw-points.

DISCUSSION

The direction and amount of movement are important factors in LFIO stability. The stability of downward movement with advancement is reported as very low, but it is controversial.[1,11] The aim of the present research was to examine the stress distribution on bone and fixation systems in CCWR by posterior downward and advancement movement of the maxilla with 2.0 mm and 1.5 mm diameter fixation systems which are routinely used in maxillofacial surgery. The study's null hypothesis was that 1.5 and 2.0 mm osteosynthesis systems have similar stability in grafted cases. Our study's findings indicated the importance of graft use; however, there is no clear evidence for the type of osteosynthesis systems regarding stability in the posterior downward movement of the maxilla. In grafted models, 1.5 and 2.0 mm osteosynthesis systems stress values were similar. Graft application has reduced the stress on bone

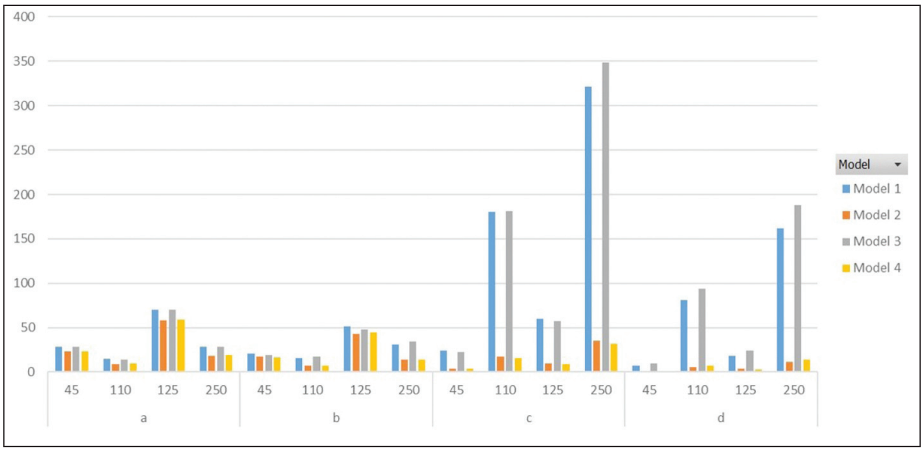

FIGURE 8: von Mises stress values (N/mm²) of standardized plate evaluation points.

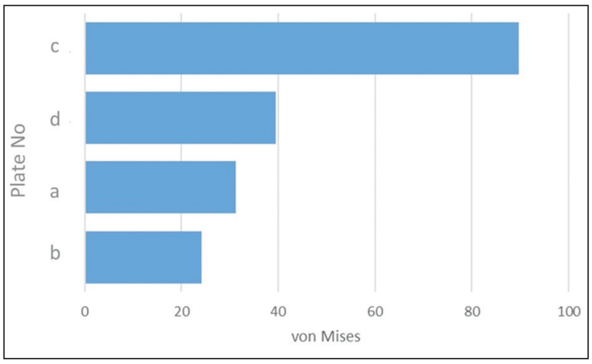

FIGURE 9: Mean von Mises (N/mm²) values of plate-points.

and osteosynthesis systems and caused the force to be transmitted vertically. The highest stress values were measured on the non-grafted model (1.5 mm osteosynthesis system) and the lowest on the grafted model (2.0 mm osteosynthesis system).

Reyneke et al. examined the stability of clockwise and CCWR of the maxillomandibular complex in a retrospective study and stated that both movements were stable.[12] However, the stability of posterior downward movement was relatively low (mean posterior nasal spine downward movement was 1.07 mm). Also, Erkmen et al. reported the postoperative safety of CCWR of the maxillomandibular complex. In both studies, CCWR was achieved by maxillar anterior impaction.[8,12] To our knowledge, no study has investigated the posterior downward movement with the advancement of the maxilla.

There is a clear correlation between orthognathic surgery and bite force. Several studies demonstrated that the bite forces decrease in the early postoperative period and increase with recovery, lasting 3 months to 2 years.[13,14] The stress on osteosynthesis systems and bone increases as bite force increases. This was accepted as one of the main causes of early relapse.[11,13-15] The majority of postoperative relapse occurs in the early postoperative period (6 to 8 weeks).[16] Harada et al. established the early postoperative occlusal forces as 41.5-60.8 N for females and 29.4-69.6 N for males in the postoperative second week.[13] Another work on Le Fort I with FEA accepted similar bite forces to mimic the early and late stages of the postoperative period.[11]

In order to simulate the different terms of the healing process, the current study looked at various bite forces. Also, incisor and molar forces were applied separately to observe the isolated effect of the masticator forces. This study showed that in the early postoperative period (45 N incisor force and 110 N molar force), both 1.5 mm and 2.0 mm osteosynthesis systems with or without graft could maintain stability. A strong link between the amount of maxillary advancement and postoperative surgical stability is also well documented. Advancement of the maxilla diminishes the amount of bone contact. Postoperative stability may decrease as soft tissue grows into these spaces if no bone grafts are inserted. Bone grafts act as a barrier to soft tissue growth and support the optimum bone healing process.[17]

Bone healing has limitations. More than a 3 mm gap between the osteotomy lines could be the result of inadequate regeneration.[18] Although this is not a physical problem in the early postoperative period, the healing process should be considered. Soft tissue penetration from these gaps results in ass decreased postoperative stability. Bone grafts act as a barrier and support the healing process.[17] Also, patients with inferior repositioning exceeding 5 mm and advancement exceeding 6 mm without bone grafting have a higher recurrence tendency.[8]

The safety of fixation in orthognathic surgery depends on the stability of the screws.[19,20] Various types of osteosynthesis protocols have been reported. An L-shaped 2.0 mm or 1.5 mm diameter plate-screws are the most common.[21] In the present study, the highest stresses were accumulated on the F and H screws and plate c-point. If the load increases on plates, the posterior one may break. However, the breakage of miniplates following LFIO is very infrequent. Nevertheless, loads on the screws are extremely important as the stresses are transferred directly to the bone, and if the load on the bone increases; resorption, screw loosening, and failure may occur. Then the result is an unstable or moveable maxilla.[7,11,21]

Oblique and horizontal forces have been established as a risk regarding LFIO stability.[20] Ataç et al. showed that these forces create more stress formation than vertical forces in osteosynthesis and bone.[20] The current study found that non-grafted models distributed the stress obliquely to the anterior bone-contact region coming from posterior vertical occlusal forces. That could cause more stress on bone and adversely affect the stability of LFIO. The graft provides perpendicular transmission of stress to the viscerocranium. In addition, there is a notable difference in the accumulated stress between the grafted and non-grafted models.

The main weakness of this study was that the displacement measurements of transport segments and osteosynthesis systems were not performed.

CONCLUSION

The findings clearly indicate that a bone graft should be applied in 4 mm or more downward movement of the maxilla posteriorly. Therefore, less stress accumulation was observed in both bone and osteosynthesis systems. The second significant finding was that 1.5 mm diameter fixation systems could be used safely in grafted cases.

Source of Finance

During this study, no financial or spiritual support was received neither from any pharmaceutical company that has a direct connection with the research subject, nor from a company that provides or produces medical instruments and materials which may negatively affect the evaluation process of this study.

Conflict of Interest

No conflicts of interest between the authors and / or family members of the scientific and medical committee members or members of the potential conflicts of interest, counseling, expertise, working conditions, share holding and similar situations in any firm.

Authorship Contributions

***Idea/Concept:** Sina Uçkan, Muazzez Süzen, Kıvanç Berke Ak; **Design:** Sina Uçkan, Muazzez Süzen, Abdullah Özel, Kıvanç Berke Ak; **Control/Supervision:** Sina Uçkan, Muazzez Süzen, Abdullah Özel; **Data Collection and/or Processing:** Muazzez Süzen, Kıvanç Berke Ak; **Analysis and/or Interpretation:** Sina Uçkan, Muazzez Süzen, Abdullah Özel, Kıvanç Berke Ak; **Literature Review:** Sina Uçkan, Muazzez Süzen, Kıvanç Berke Ak; **Writing the Article:** Sina Uçkan, Muazzez Süzen, Abdullah Özel, Kıvanç Berke Ak; **Critical Review:** Sina Uçkan, Muazzez Süzen, Abdullah Özel; **References and Fundings:** Sina Uçkan, Muazzez Süzen; **Materials:** Sina Uçkan, Muazzez Süzen, Kıvanç Berke Ak.*

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